

THE MEASUREMENT OF ENVIRONMENTAL TOBACCO SMOKE IN 585 OFFICE ENVIRONMENTS

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In order to provide information on levels of environmental tobacco smoke (ETS) in office environments during 1989, a total of 585 offices was sampled for a number of factors, including respirable suspended particles (RSP), nicotine, carbon monoxide, carbon dioxide, room size, average number of room occupants, and number of cigarettes consumed. Each data set was collected over a one-hour sampling period. Discriminant analysis of the data collected showed a group of rooms used for light smoking (59.9% of total smoking rooms) was not significantly different from the nonsmoking rooms, in terms of the variables which contributed to the predictive ability of the model (RSP and nicotine). These light-smoking rooms overlapped somewhat with the heavy-smoking rooms, suggesting other variables not measured here might contribute to this model, such as air change rates or outside air intake volumes. This leads to the possibility that a range of smoker densities could be established inside which indoor air quality will not be significantly affected, thus reflecting the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 62-89, which shows that with good ventilation acceptable air quality can be maintained with moderate amounts of smoking. Statistical analysis also showed overall levels of ETS in offices to be considerably lower than estimated in work ten years previously, and that carbon monoxide is only weakly influenced by smoking activity. Carbon dioxide measurements taken in each room did not correlate significantly with RSP, nicotine, or carbon monoxide, and there were significant relationships between smoker density, RSP, and nicotine, respectively.

INTRODUCTION

Given the present-day concerns in the U.S. society about exposure to environmental tobacco smoke (ETS), it is important that measurements used to assess exposure to this substance are representative

of conditions existing in modern office environments.

Numerous studies have measured levels of various components of ETS in both the home, workplace, and other public places. Repace and Lowrey (1980, 1982)

presented results of field measurements made in non-office environments (bars, restaurants, bingo games, dinner dances, bowling alleys, sports arenas, waiting rooms, etc.), as well as experimental results in office type environments with high smoking rates (32 cigarettes smoked in 49 min). Respirable suspended particles (RSP) levels were found as high as $697 \mu\text{g}/\text{m}^3$ in the non-office environments. In some office experimentation, an equilibrium of $1947 \mu\text{g}/\text{m}^3$ of RSP was attained with a time constant (τ) of 14 min. They used data from these two papers to derive a mathematical model to estimate average RSP concentrations of $200 \mu\text{g}/\text{m}^3$ in office environments where smoking was allowed (Repace and Lowrey 1987).

These papers are frequently referenced by other workers, and were extended by Repace and Lowrey to compute a "quantitative estimate of nonsmoker lung cancer risk from passive smoking" (1985a), and then "an indoor air quality standard for ambient tobacco smoke based on carcinogenic risk" (1985b). References to one or both of the first two papers are found within much literature on the subject of ETS that has been published since (Collishaw et al. 1984; Samet 1988; Meisner et al. 1989; Wells 1986; Sterling 1982; Wells 1989). These include some papers published as recently as 1989. In addition, the U.S. Environmental Protection Agency (USEPA 1990) currently includes references to these two papers in their Draft Guide to Workplace Smoking Policies. This document has not been formally released however, and is still in the review process.

There are no data in these papers on field measurements of ETS in office workplace environments; however, they have been referenced in many cases to argue that ETS is the major particulate component of indoor air, and hence smoking should be eliminated from the office environment. At present, research that measures components of ETS in discretionary smoking office environments has been limited—most studies contain small data sets thereby preventing precise statistical analyses. Examples of these relatively small scale ETS studies focusing on RSP where smoking was discretionary include Meisner et al. (1989), where RSP ranged up to $80 \mu\text{g}/\text{m}^3$, with a mean of $34 \mu\text{g}/\text{m}^3$. Also, Sterling et al. (1987) reported mean RSP levels of $37 \mu\text{g}/\text{m}^3$ in smoking permitted areas in their Building Performance Database (BPD). Finally in this vein, Oldaker (1990) measured RSP levels in a range of offices and reported mean RSP levels of $126 \mu\text{g}/\text{m}^3$ (mean Ultra Violet Particulate Matter [UVP] levels of $27 \mu\text{g}/\text{m}^3$). In any case, overall ETS levels have likely changed during the

past decade due to improved ventilation rates and changing patterns of smoking in the U.S.

There is still a need for more study on all aspects of ETS in modern offices where smoking is allowed, especially in a larger variety of office environments sampled with the same methodology to highlight the influencing factors.

In an effort to provide contributory data on ETS components in office atmospheres, and to build on our understanding of which factors influence ETS levels, this study sets out to measure a series of parameters related to, or influencing, ETS in a very large sample of offices, using identical methodology in each. This provides us with up-to-date information on ETS in contrast with the data collected a decade previously.

METHODS AND MATERIALS

Obstacles which have prevented the collection of data as extensive as this before may have been: a) cost—since travel to and time in each office building constitutes a significant portion of a budget for this work; and b) access to each building. (Unless building owners or employers see some personal benefit, they are unlikely to allow their staff or tenants to be disturbed for air sampling exercises.) Each building requires individual persuasive visits allowing technicians into the building. This would normally be a prohibitive effort if the objective is to sample from hundreds of buildings.

Both cost and building access problems are eased by the nature of the indoor air diagnostic work routinely conducted by HBI. Access to many buildings is negotiated during the course of indoor air surveys allowing the ETS study to be added on to each routine indoor survey, with additional expense limited to a brief extra time period and analytical costs. In this manner, it was possible to survey several hundred buildings within practical cost constraints and without access difficulty.

During the visit to each building, the primary indoor air survey includes, as a minimum, visual inspections of the internals of each air handling system and measurements for a range of air contaminants throughout the building space. This survey is separate from the ETS study each building was subjected to, and no efforts are made in this paper to coordinate the results from the main air quality survey and the ETS studies.

The nature of this process dictates the buildings which were surveyed. Some were surveyed because of indoor air quality complaints by occupants. The majority were sampled, however, during the course

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of routine proactive monitoring visits to buildings perceived as generally healthy. We have no reason to suspect the buildings in this sample are not representative of office buildings throughout North America.

Unoccupied areas of buildings (e.g., areas under renovation), garages, stairwells, industrial areas, and outside terraces were avoided, although cafeterias and some areas designated as smoking lounges were included. A minimum of two ETS sample sets were taken in each building, and while it cannot be claimed that the occupants were unaware of the sampling activities, they were not informed that the sampling was related to ETS.

Data set collection procedures

A one-hour time period was allocated to each ETS sampling set. During this period, the field technician did not leave the space selected for sampling. Each sampling set consisted of the following information:

General:

Inspector I.D.
Client name
Building address
Overall building size
Number of stories

Specific to sampling set:

Type of business and work activity
Location (floor/room)
Room configuration details (partitions, supply, and return outlets)
Room size (m^2)
Number of people in room (average)
Number of cigarettes smoked
Respirable suspended particles ($\mu g/m^3$)
Carbon dioxide ($\mu L/L$)
Carbon monoxide ($\mu L/L$)
Nicotine ($\mu g/m^3$)
Temperature ($^{\circ}C$)
Relative humidity (%).

Smoking density was then calculated for the hour sampling period by dividing the number of cigarettes consumed in the hour by the room size, to give $cig/m^2 \cdot h$.

The methodologies used for the air sampling were as follows:

Respirable airborne-particle counts were made using a piezoelectric microbalance that measured particles

in the 0.01 to $3.5 \mu m$ size range. Flow rate through the piezobalance was periodically checked at $1 L/min$ with a bubble flow meter, and the sensor was cleaned with alcohol swabs after every five measurements. The unit is factory-calibrated with diluted welding fumes which have shown equivalence to indoor RSPs to $\pm 10\%$. The lower detection limit was set at $10 \mu g/m^3$.

Carbon dioxide levels were measured using a non-dispersive infrared absorption portable gas analyzer. Accuracy is $\pm 2\%$ over full scale. Periodic calibration of the instrument was with a factory-supplied span gas of $5000 \mu L/L$ CO_2 . Zero was set with dry nitrogen gas and the lower detection limit was set at $50 \mu L/L$.

Carbon monoxide concentrations were measured using a controlled potential electrolysis detector, accurate to 10% full scale. Periodic calibration of the instrument was with a factory supplied span gas of $50 \mu L/L$ carbon monoxide. The minimum detection limit was set at $1 \mu L/L$.

Each of the above three parameters, as well as temperature and relative humidity, was measured in real-time and recorded ten times during the hour period. The real-time measurements and the average of the ten measurements were recorded in a standard field log, along with calibration data.

Airborne nicotine was measured after USEPA (1989) with a personal universal flow sampling pump drawing air through unfiltered XAD4 absorbent resin tubes. Samples were analyzed with gas chromatography. Results are expressed in total micrograms converted to $\mu g/m^3$, and the detection limit for our sampling rate of $1 L/min$ for a one-hour period is given as a conservative $1.6 \mu g/m^3$ of air.

Statistical methods

General statistics. Statistical methods were used for the purposes of data description and correlation assessment between specific variables. Graphical methods were also used to evaluate relationships between specific variables.

The main goal of the statistical analysis was to evaluate differences between smoking-observed and nonsmoking-observed areas. To evaluate these potential group differences for variables such as RSP, nicotine, CO_2 , and CO , *t*-tests were used.

Discriminant analysis. The goal of discriminant analysis (Karson 1982) was to predict group membership from several predictor variables. With these data, the discrete variable defining group membership was the type of room—either smoking-observed or nonsmoking-observed. Room type was entered into

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discriminant analysis with several predictor variables such as RSP and nicotine.

The discriminant analysis methodology used here is a stepwise procedure; it initially enters the most significant variable for predicting group membership, as defined by specific statistics, and proceeds to enter new variables into the model until the inclusion of additional variables does not increase prediction ability. There are other methods available that will determine the best predictor model, such as backward elimination. In many cases, however, each method will result in the same final model.

The discriminant function, on the basis of the input variables (e.g., CO₂, RSP, and nicotine levels), decides on whether a room should be classified as a smoking or a nonsmoking room (Table 3). The results of the discriminant analysis are then compared to actual room status.

Assuming that there is a significant difference between a nonsmoking and a smoking environment, then discriminant analysis should produce the following: (1) a discriminant model that is significant, and (2) a model which differentiates between smoking-observed and nonsmoking-observed rooms.

Software. A computer package by BMDP Statistical Software Inc. (#BMDP 7M) was used to generate this discriminant analysis. Standard statistical packages were used to produce the tables, graphs, and descriptive statistics.

RESULTS

Descriptive statistics

The final mix of building types surveyed is shown in Table 1. Since the establishment of designated smoking and nonsmoking areas may or may not be respected by occupants, and because even a smoking

lounge may contain no smokers during our sampling period, it is not possible to classify areas as definitely smoking or nonsmoking. Instead, we can classify areas based on the smoking activity observed to be in place during the sampling period. For information, however, 20 rooms sampled were noted as designated smoking lounges. There were 254 nonsmoking-observed and 331 smoking-observed data sets, giving a total of 585 data sets.

Figures 1 through 4 show frequency distributions for four parameters, divided into smoking-observed and nonsmoking-observed groups. These frequency distributions illustrate the basic features of the raw data.

Table 2 displays the mean and standard deviation of, among others, the following variables: (1) RSP, (2) nicotine, (3) CO₂, (4) CO, and (5) room size. These statistics are shown for the overall data set, and are also categorized by room type (observed smoking activity), smoking or nonsmoking.

To explore in more detail the relationships between some of these factors, correlation coefficients were calculated between various parameters. Strong correlation exists between the following variables: RSP and smoking density ($r = 0.5180$, $p < 0.01$); nicotine and smoking density ($r = 0.7007$, $p < 0.01$); RSP and nicotine ($r = 0.7345$, $p < 0.01$).

Poorer correlations are calculated between the following variables: carbon monoxide and smoking density ($r = 0.1792$, $p < 0.01$); carbon dioxide and RSP ($r = 0.1763$, $p < 0.01$); carbon dioxide and nicotine ($r = 0.0841$, $p < 0.05$). It should be noted that the small p -values imply a nonzero correlation which does not mean a strong correlation. Correlations less than 0.2 should be viewed as relatively weak.

Table 1. Numbers of office types sampled.

General Commercial Office Areas	340
Banking Offices	152
Cafeterias	62
Newspaper Offices	14
Institutional (church, hospital, correctional or educational)	17
Total	585

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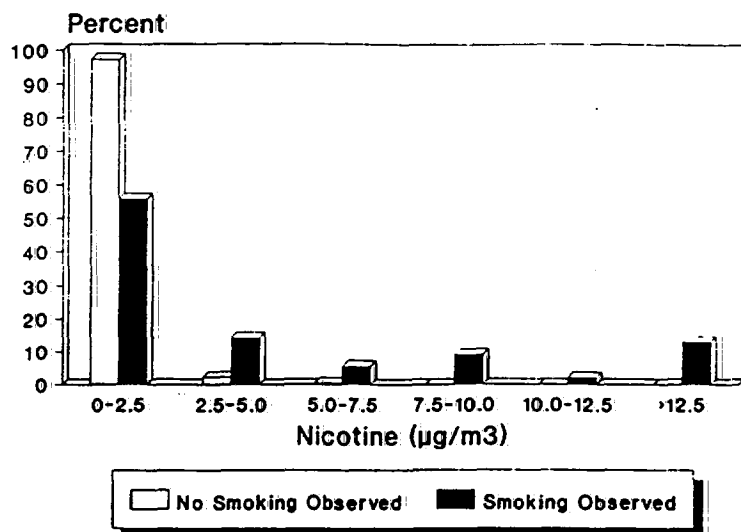


Fig. 1. Frequency distribution for nicotine measured in 585 office buildings with and without observed smoking.

Discriminant analysis

As indicated above, t-test results suggest that there is a significant difference between smoking and non-smoking rooms when considering the variables RSP ($p < 0.01$), Nicotine ($p < 0.01$), and CO ($p < 0.05$). However, there is serious overlap between the fre-

quency distributions of smoking rooms and non-smoking rooms, particularly on the variables CO and RSP.

All factors in Table 2 were entered into the discriminant analysis (except number of cigarettes smoked). Smoker density was not entered into the

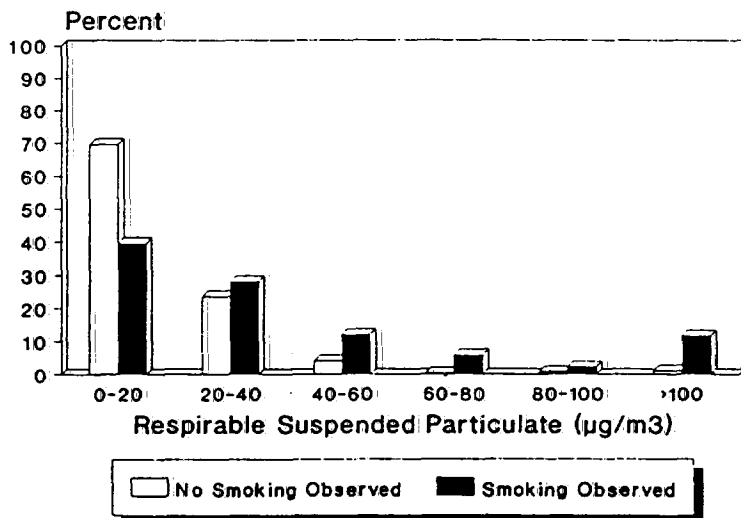


Fig. 2. Frequency distribution for respirable suspended particles measured in 585 office buildings with and without observed smoking.

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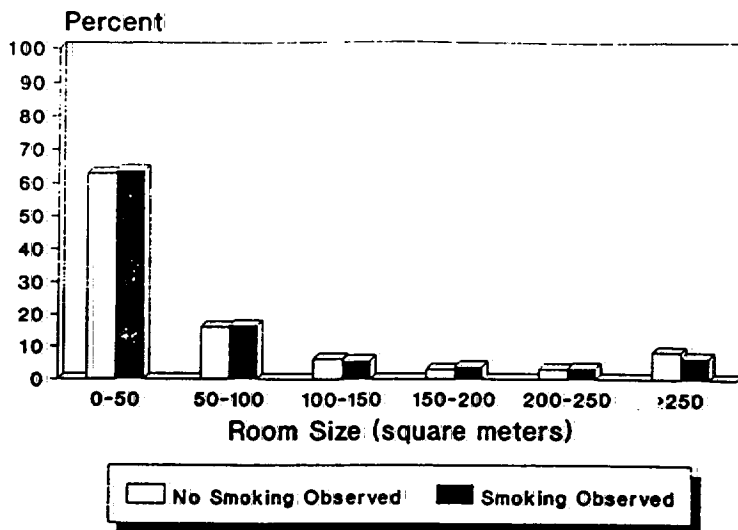


Fig. 3. Frequency distribution for room sizes of 585 office environments with and without observed smoking.

analysis since it is directly related to room type definitions— smoker density equal to zero is defined as a nonsmoking room and smoker density not equal to zero is defined as a smoking room. The discriminant analysis was significant and the variables RSP and nicotine were the only variables entered into the model. The discriminant analysis did not enter the

variables CO and CO₂, nor the variables relating to room size and occupant density. All of these unentered variables do not improve the ability of the discriminant function to classify the rooms as smoking or nonsmoking.

Table 4 displays the ability of the selected model to predict room type properly. The selected model

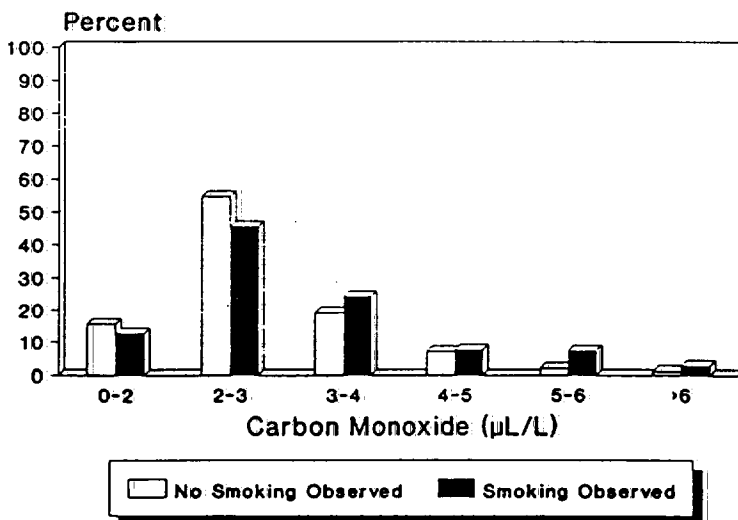


Fig. 4. Frequency distribution for carbon monoxide measured in 585 office environments with and without observed smoking.

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Table 2. The mean (Standard Deviation) of variables grouped by observed smoking activity.

Observed Smoking Activity	RSP* ($\mu\text{g}/\text{m}^3$)	Nicotine* ($\mu\text{g}/\text{m}^3$)	CO ₂ ** ($\mu\text{L}/\text{L}$)	CO* ($\mu\text{L}/\text{L}$)	Room Size** (m^2)	= of People	= of Cigarettes Smoked
Non-Smoking	20 (17.6)	0.2 (0.8)	591 (159)	3.1 (0.90)	107 (231)	7.9 (15.7)	0.0 0.0
Smoking	46 (56.9)	6.7 (14.8)	595 (167)	3.4 (1.12)	83 (134)	7.9 (12.6)	5.9 (12.8)
Totals	35 (44.4)	3.8 (11.2)	593 (163)	3.29 (1.03)	93 (182)	7.9 (14.0)	----- -----

* Statistically significant difference between nonsmoking and smoking group.

** No statistically significant difference between nonsmoking and smoking group.

was able to classify properly 96.1% of the nonsmoking rooms as nonsmoking. However, only 41.4% of the smoking rooms were classified as smoking; 58.6% of the smoking rooms were classified as nonsmoking. Overall, 65.1 of the cases were properly classified.

Table 5 displays the mean and standard deviation of selected variables in the ETS data set. These variables are grouped according to observed status, either smoking or nonsmoking, and status provided by discriminant analysis. One possible combination, ob-

Table 3. Classification functions which determine model group membership, derived from discriminant analysis of the sample data.

Group	Constant	RSP	Nicotine
Nonsmoke	-0.8916	0.0202	-0.0557
Smoke	-1.2628	0.0284	-0.0269

Table 4: Classification of observations into smoking and nonsmoking groups by the discriminant analysis model based on sample results (the percentage of correct classifications is also shown).

Observed Status	Percent Correct	Model Status	
		Non Smoke number of sets	Smoke number of sets
Nonsmoke	96.1	244	10
Smoke	41.4	194	137
Total	65.1	438	147

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Table 5. The mean (Standard Deviation) of selected variables shown for groups defined by their status as observed in the field during sampling and the discriminant analysis model based on sample results.

Observed Status	Model Status	RSP* $\mu\text{g}/\text{m}^3$	Nicotine** $\mu\text{g}/\text{m}^3$	CO_2^* ($\mu\text{L}/\text{L}$)	CO^* ($\mu\text{L}/\text{L}$)	Smoking Density** $\text{cig}/\text{m}^2\cdot\text{hr}$
Nonsmoke	Nonsmoke	17.18 (9.5)	0.1 (0.6)	584 (153)	3.1 (0.8)	0.0 (0.0)
Smoke	Nonsmoke	19 (9.2)	0.9 (1.9)	566 (170)	3.3 (1.0)	0.075 (0.075)
Smoke	Smoke	85 (71.8)	14.8 (20.4)	636 (154)	3.6 (1.3)	0.30 (0.35)

*No statistically significant difference between Nonsmoke/Nonsmoke and Smoke/Nonsmoke. All other differences are statistically significant.

**Statistically significant differences between all groups.

served-status nonsmoking/model-status smoking, is not included since this combination only contains ten observations. The data show that for groups defined by observed-status nonsmoking/model-status nonsmoking and observed-status smoking/model-status nonsmoking, there is no statistically significant difference between group means for the variables CO, CO_2 , and RSP. The group smoking-observed status/smoking-model status is significantly different when considering nicotine and smoker density. This difference is slight for the groups nonsmoking-observed status/nonsmoking-model status and smoking-observed status/nonsmoking-model status.

DISCUSSION

Discriminant analysis

The most significant results from the discriminant analysis are the following:

- (1) RSP and nicotine contribute to the prediction of room type—smoking or nonsmoking.
- (2) most (96.1%) nonsmoking rooms are classified as nonsmoking rooms, demonstrating very little evidence of ETS spillover from smoking areas, and
- (3) a significant number (58.6%) of total smoking rooms are classified as nonsmoking rooms.

Table 5 suggests that smoking rooms can be separated as "light" or "heavy". The light-smoking rooms appear equivalent to nonsmoking rooms when considering, in a multivariate context, the important

factors of RSP and nicotine. The heavy-smoking rooms do have elevated levels of nicotine and RSP. This indicates that there may be a rough working range of smoker density in which smoking activity does not seem to influence ETS levels significantly, as measured by RSP and nicotine.

This analysis goes part-way towards identifying what this range might be in that the mean of the light smoking range is $0.075 \text{ cig}/\text{m}^2\cdot\text{h}$ and the median figure is $0.048 \text{ cig}/\text{m}^2\cdot\text{h}$. There is considerable overlap, however, between the two types of smoking groups in Table 5. The median of the heavy-smoking rooms is $0.143 \text{ cig}/\text{m}^2\cdot\text{h}$ with 20% of the heavy-smoking rooms below the median of the light-smoking rooms, and 13.4% of the light-smoking rooms above the median of the heavy-smoking rooms. This suggests that other variables which were not fully characterized in this work, such as outside air ventilation and/or air change rates, need to be considered in more detail when determining the impact of smoking in the room environment. One can see, however, that a realistic smoking density in properly ventilated rooms might be somewhere between 0.05 and $0.1 \text{ cig}/\text{m}^2\cdot\text{h}$, or between 5 and 10 cigarettes per hour in a 100 m^2 room.

Other pertinent data

These 585 data sets reveal some other interesting information. If one examines the absolute levels of items of particular concern, such as nicotine, RSP

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and carbon monoxide, they show relatively conservative values. For instance, most of the RSP data in smoking-observed areas show levels well under that reported in Repace and Lowrey's early papers (1980, 1982); in general, about four times less than their mathematical model predicted for office environments of $200 \mu\text{g}/\text{m}^3$ (Repace and Lowrey, 1987). In this model, they assumed an occupancy of 7.53 persons/100 m^2 , one third of them smoking at an average rate of 2 cig/h (5.02 cig/100 $\text{m}^2\cdot\text{h}$). In this study, in observed-smoking areas, mean RSP levels of $46.37 \mu\text{g}/\text{m}^3$ were measured with a mean occupancy of 9.57 persons per 100 m^2 , and an average observed-smoking rate of 7.14 cig/100 $\text{m}^2\cdot\text{h}$. In fact, only eight data sets showed RSP values above this model value of $200 \mu\text{g}/\text{m}^3$.

Our measurements of RSP and nicotine also tend to match levels reported in other recent work by Meisner et al. (1989) and Eatough et al. (1989a). Ogden et al. (1990) found ETS contributes approximately 50% to RSP which mirrors almost exactly our findings in that mean RSP levels in nonsmoking-observed areas were approximately half those in smoking-observed areas.

There are statistically significant differences between smoking-observed and nonsmoking-observed areas for RSP, nicotine, and CO. While not statistically significant ($p \geq 0.10$), our data set contained smoking-observed rooms with smaller sizes than nonsmoking rooms, suggesting that smokers in modern office environments may be confined to smaller rooms than nonsmokers. This possibility might justify further work, perhaps examining smokers/nonsmokers room sizes, separate from designated smoking lounges.

A clear relationship was observed between RSP and nicotine, which is not surprising in light of other studies. These studies were summarized by Eatough et al. (1989b), and show that nicotine/RSP ratios vary depending on overall ETS levels and tend towards that found in pure sidestream smoke at the highest levels of measured nicotine and RSP.

Although it is possible to identify two different groups (smoking and nonsmoking) by examining the carbon monoxide results, the distinction is not clear enough to characterize the relationship between smoking density and carbon monoxide concentrations. For instance, it was not possible to extrapolate properly the data to identify what smoking density might be associated with CO concentrations higher than the EPA ambient 24 h maximum of $9 \mu\text{L}/\text{L}$, although it would appear to require a smoker density much greater

than typical in a "discretionary smoking" office environment.

This shows that carbon monoxide is a poor indicator for ETS levels found in typical conditions. This is in contrast to Cain and Leaderer's work (1982) in experimental chambers which showed wide variations in carbon monoxide concentrations under different smoking conditions. Lower, more typical smoking rates, and larger spaces allowing for faster diffusion of CO may explain why this gas is not as good a predictor in normal offices as it is in experimental chambers.

Improved resolution for carbon monoxide (measured to $\pm 1 \mu\text{L}/\text{L}$ in this study), and a lower detection limit for nicotine (set at $1.6 \mu\text{g}/\text{m}^3$ for this study), and RSP (set at $10.0 \mu\text{g}/\text{m}^3$) may be thought to allow for different conclusions to be drawn from the statistical analysis. However, a sensitivity analysis was performed with the discriminant analysis by setting different values for nicotine and RSP at the detection limits. For example, on a subsequent evaluation of the data with discriminant analysis, all nicotine and RSP values below the detection limit were set to zero. This produced little or no difference in the results obtained from the discriminant analysis. This strongly suggests that improved detection techniques would not change the results drawn from this study, including those conclusions concerning spillover from smoking areas.

Carbon dioxide is frequently used as an indicator of ventilation rates, and furthermore, since carbon dioxide levels are related to the number of occupants and the size of the space they occupy, these factors were also included in an attempt to establish a general ventilation status for each data set. No relationship was subsequently observed, however, between components of ETS and these factors as measured during these surveys. This does not mean that there is no relationship between total outdoor air intake for the building and overall ETS levels. But it means that local measurement of CO_2 needs to be interpreted carefully if it is to be used as an indicator of ventilation, and that it may show considerable spatial variations in a building, depending on local floor and air handling zone characteristics. This study did not examine in detail local room aspects of ventilation such as air change rates or airflow through local diffusers which may correlate much more strongly with local ETS levels. Alternatively, average levels of ETS throughout a building may also correlate with total outdoor air intake.

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CONCLUSIONS

These 585 measurements of some components of ETS and other related parameters sampled during 1989 suggest overall concentrations of ETS in typical office workspaces to be considerably lower than estimated ten years previously. Some parameters, such as carbon monoxide, appear to be only weakly related to smoking activity. Discriminant analysis shows that when "blindfolded" for presence or absence of smokers, in most cases realistic smoking levels do not significantly influence the aspects of air quality that were measured, and spillover from smoking areas into nonsmoking areas appears to be minimal. This work further reinforces the position the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) has taken on ETS in office buildings in ASHRAE Standard 62-89 (1989), in that acceptable air quality can be maintained in properly ventilated offices with a moderate amount of smoking, even without smoker segregation. These data help to further define the limits of moderate smoking.

Further work to achieve this goal should address room air exchange and ventilation rates, and their relation to ETS. This might best be achieved with the use of tracer gas instrumentation. This ventilation data when combined with ETS component measurements will give us a better understanding of the relationships between smoking and ventilation in modern offices. Other influencing factors may also include furnishing types and room size, which could be studied in more detail.

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